ALLISON CERAMIC VANE EFFORTS

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INTRODUCTION

A major overall goal of the Department of Energy (DOE) Advanced Turbine System (ATS) Program is ultra-high efficiencies for gas turbine plants. For industrial turbine systems, the goal is a 15% improvement in efficiency. A 15% goal is beyond the typical evolutionary increase in industrial turbine plant efficiencies. The ATS participation of the DOE is stimulating the development of turbine technologies to achieve this step improvement in turbine performance. Development of uncooled ceramic airfoils to reduce chargeable cooling of metallic vanes or blades can facilitate achievement of the efficiency goals of the ATS Program and can also increase turbine power output.

OBJECTIVE

An objective of the DOE/Allison ATS Program is to evaluate and develop ceramic airfoils for industrial gas turbines, in particular, the commercial Allison 701-K turbines resulting from the ATS program. Ceramic structural turbine components are not yet commercially available, although the development of ceramics for gas turbines has been pursued for about 20 years. Much of the work to date has been directed to small automotive gas turbines (Khandelwal, 1991; Retter, et al, 1995). Some recent efforts (van Roode, et al, 1994, 1995, 1996, 1997) have a goal to demonstrate first-stage ceramic vanes and blades and a ceramic combustor liner in a current generation industrial gas turbine.

There are additional issues for application of ceramic airfoils in industrial turbines compared to small automotive turbines, the application for most past ceramic turbine development. These include longer required part lifetimes (up to 30,000 hr) and more severe thermal shocks during emergency shutdown of industrial turbines (Wenglarz, et al, 1996).

Another issue for introduction of ceramic components into commercial turbines is high initial cost until a sufficient production volume can lower manufacturing costs. Consequently, design to minimize fabrication costs is important to ensure that economic benefits of increased turbine performance for ceramic airfoils are not offset by high initial costs.

The following discusses efforts to evaluate and develop ceramic vanes for Allison ATS turbines and describes how the issues are being addressed.

APPROACH

The overall program approach consists of demonstrating first-stage ceramic vanes in a current generation Allison 501-K turbine and demonstrating second-stage ceramic vanes in the Allison ATS turbine rig. The 501-K turbine demonstration should provide a stepping stone to implementation of ceramic vanes in the ATS engine (701-K) because of comparable thermal environments for the ceramic vanes in the two engines. The ATS second ceramic vane average and peak gas temperatures and emergency shutdown thermal shocks are somewhat less severe than those for the 501-K first ceramic vanes. Economic benefits to an end user will be compared for the ATS turbine with ceramic second-stage vanes and the all-metallic ATS turbine.

PROJECT DESCRIPTION

501-K Turbine Ceramic Vane Effort

The following outlines the tasks to demonstrate first-stage ceramic vanes:

- Design and analyses of ceramic vanes and mounting hardware for retrofit into an Allison 501-K turbine.

- Ceramic vane procurement and mount fabrication.

- Thermal shock proof tests of the ceramic vanes.

- Proof tests of the vanes and mounting hardware in a test engine.

- Demonstration vanes and mounts in a long-term (up to 8000 hr) 501-K turbine run at a commercial site.

About 4000 hr of the 501-K turbine demonstration are expected to be completed before starting the turbine rig tests in the ATS second ceramic vane effort.

ATS Turbine Ceramic Vane Effort

The ATS turbine second-stage ceramic vane tasks are:

- Design and analyses of ceramic vanes and mounting hardware for retrofit into the Allison ATS turbine.

- Materials tests of the same ceramic as used in the 501-K turbine and other promising ceramics.

- Projection of long-term vane life using data from the materials tests.

- Procurement of vanes of best ceramic determined from the testing and analyses tasks, along with experience from the 501-K turbine effort.

- Turbine rig testing with metallic and ceramic second vanes

- Use of turbine rig test data, performance analyses, and end user economic analyses to compare performance and economic benefits for a generation plant owner/operator using the ATS turbines with metallic and ceramic second-stage vanes

RESULTS

501-K Turbine Ceramic Vanes

Vane Design: The 501-K turbine first-stage ceramic vane design is shown in Figure 1. The design was evaluated by thermal and stress analyses and interaction with ceramic suppliers to minimize fabrication costs. The ceramic vane consists of an airfoil with simple platforms bounding the inner and outer flow-path surfaces. The platforms seat in circumferential grooves of inner and outer metallic mounts and are not rigidly mounted.

Steady-State Stresses: The primary source of stress in the ceramic vane at maximum continuous turbine power conditions was determined to be the combustor temperature pattern. The nonrigid mounting of the vane contributes to relatively small bending stresses from the aerodynamic loads. For the AlliedSignal AS 800 Si_3N_4 ceramic, a maximum steady stress of about 172 MPa (24.5 ksi) was calculated. A materials temperature of 1182°C (2160°F) was also calculated in the

Figure 1. 501-K turbine first-stage ceramic vane.

midspan trailing edge region of maximum steady-state stress. The calculated fast fracture probability of survival (POS) for the group of 60 vanes exceeds 99.99%.

Thermal Shock Stresses: Emergency shutdown thermal shock stresses were calculated considering the AS 800 material for the vanes. As for steady-state conditions, the location of maximum stress is the region of the midspan trailing edge. The value of this highest stress is 208 MPa (30.2 ksi) at about 0.9 sec after emergency shutdown, and the instantaneous ceramic temperature at its location is 729°C (1345°F). The calculated fast fracture POS for the vane set at emergency shutdown exceeds 99.99%.

Long-Term Materials Properties: Long-term ceramic material tests have been conducted at Oak Ridge National Laboratories (ORNL) and the University of Dayton under conditions representative of industrial turbines. Included were conditions addressing the stress rupture and retained strength requirements for the 501-K turbine ceramic vanes. Among other conditions, AS 800 specimens were exposed for durations up to 8000 hr to the maximum steady-state stress (about 172 MPa) calculated for the 501-K ceramic vane and at conservative temperatures of 1316°C (2400°F), about 134°C (240°F) higher than calculated at the location of maximum vane stress. None of the four specimens of the properly processed batch of material failed in stress rupture at these conditions. Figure 2 shows tensile strain versus time for two specimens tested for about 8000 hr under these conditions, along with data for higher stresses. Figure 3 shows as-received strength of the AS 800 ceramic and retained strength for two specimens exposed for 4500 hr to the representative 501-K vane steady-state conditions described. The retained strength was measured at 1000°C (1832°F), a conservative value compared to the materials temperature of 729°C (1345°F) calculated at the vane location of maximum emergency shutdown stress. Figure 3 indicates the AS 800 retained strength is about the same as the as-received strength of 530 MPa, which is substantially greater than the maximum emergency shutdown stress of 208 MPa.

The ceramic materials data obtained by ORNL and the University of Dayton have provided a basis for proceeding with plans for at least a half-year (about 4500 hr) 501-K turbine demonstration using AS 800 vanes. Further data and evaluations will be used to determine whether the demonstration will be extended to one-year duration.

Status of 501-K Ceramic Vane Effort: 501-K turbine ceramic vane design, drawings, and analyses have been conducted. As discussed, acceptable fast fracture stresses and probabilities of survival have been calculated for the ceramic vanes fabricated with AS 800 ceramic. Sufficient stress rupture data for that ceramic has been acquired at 501-K turbine conditions to proceed with at least a 4500-hr demonstration. Fabrication of the ceramic vanes is in process, and the drawings for the vane metal mounts are nearly completed.

ATS Turbine Ceramic Vanes

Mount Arrangement: Unlike the 501-K first vane mounts, the ATS second vanes cannot be simply supported at both ends. This is because the ATS second vanes are located between the first and second rotating blade sets and are not supported at the rotating shaft interface. The ATS metallic vanes and the retrofitted ceramic vanes must be cantilevered from the turbine casing.

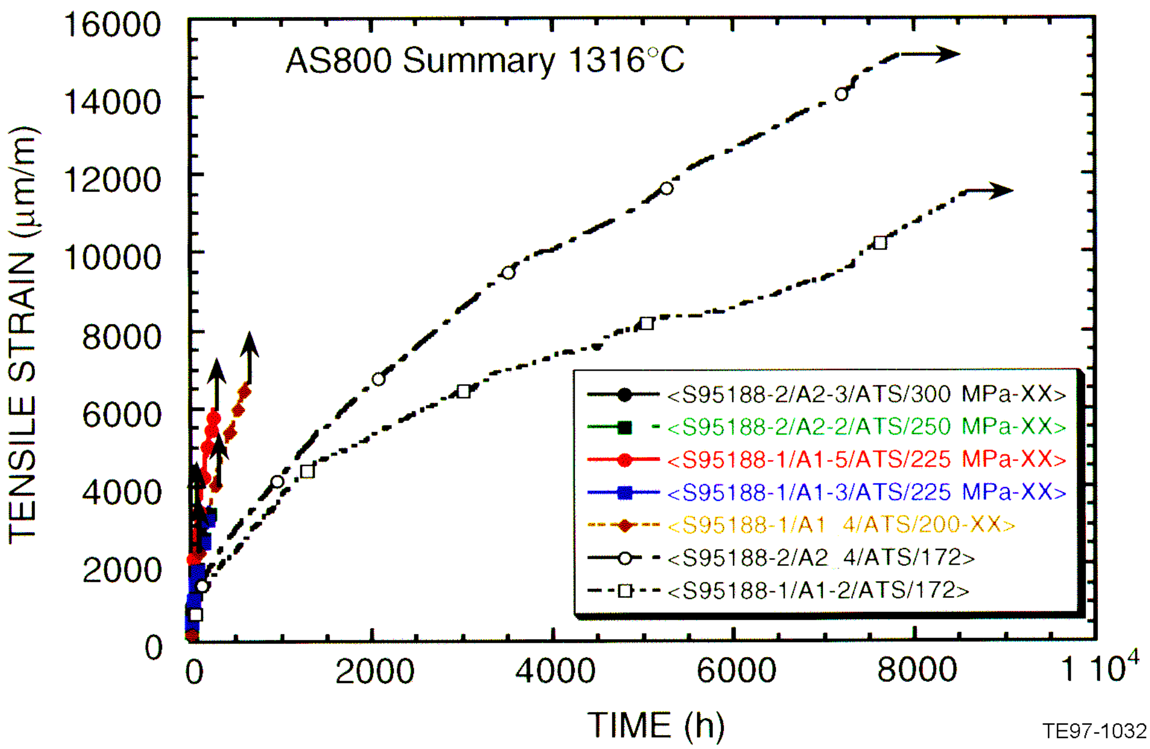

Figure 2. Stress rupture tests of AS 800 ceramic.

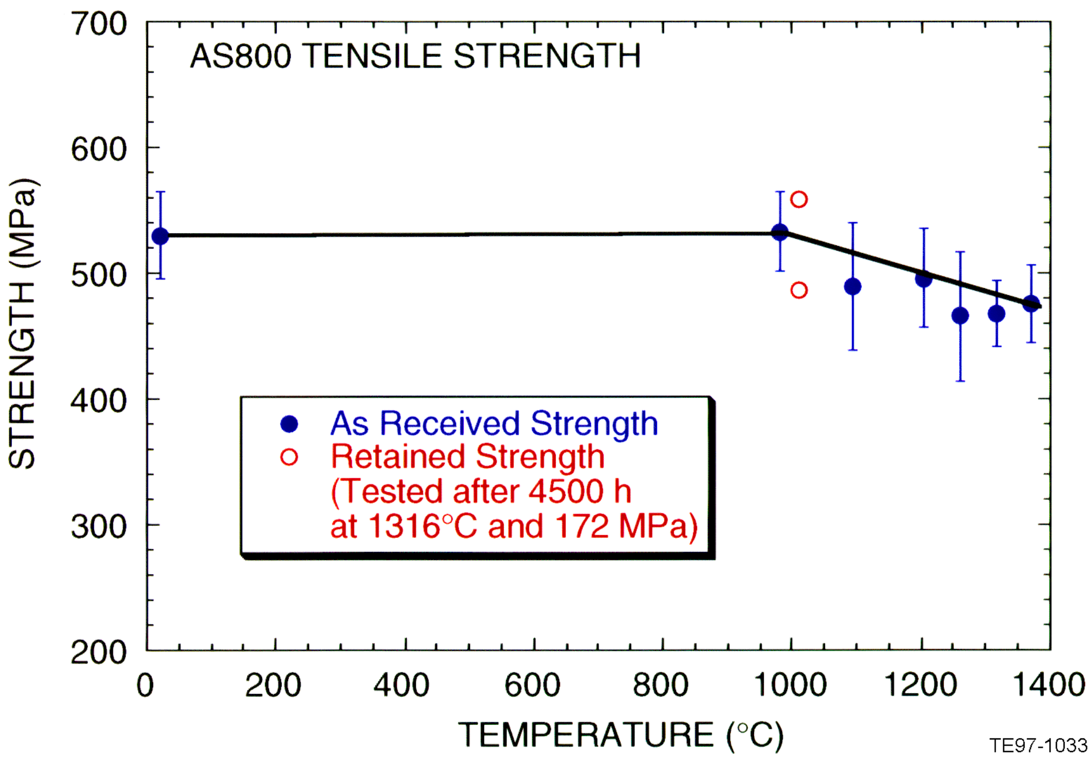

Figure 3. As-received and retained strength of AS 800 ceramic.

Vane Design Approaches: Four candidate ceramic vane design concepts for the ATS engine were defined and presented to ceramic manufacturing partners for their assessment of manufacturability and costs. The objective was to identify a vane design with the lowest practical cost at the early stage of commercial introduction, before high volume production is achieved. The simplest vane design concepts were modifications of the 501-K ceramic vane simple design to accommodate cantilevered support from one end, compared to nonrigid support of the 501-K ceramic vanes from both ends. Relative cost estimates for initial small production quantities from the vendors did show a high initial cost sensitivity to design, with a factor of up to 2.6x difference in predicted manufacturing cost between the various concepts.

Airfoil Shape Screening: Analyses have started to define an airfoil shape for ceramic ATS second-stage vanes. The ceramic airfoil must be thin enough for uniform cooling during turbine emergency shutdown, so that thermal shock stresses are acceptable. The airfoil must also be thick enough that steady-state bending stresses from aero loads are acceptable. Initial analyses indicate the challenge of satisfying these conflicting criteria for the ATS vane compared to the 501-K turbine vane. Approximate analyses indicate a factor of nearly five times greater steady-state bending moment for the ATS second vane compared to the 501-K first vane, even though the vanes are of similar scale. This is due to the cantilevered mounting, the much higher pressure ratio, and the differential pressure load below the vane lower platform for second-stage ATS vanes when compared to first-stage 501-K vanes.

Aerodynamic analyses have defined candidate vane contours with acceptable aerodynamic performance, relatively small maximum-to-trailing edge thickness ratios, and increased moments of inertia (and stiffness) to resist bending loads. Figure 4 compares two candidate outer span ceramic vane contours to the contour of the metallic second vane (top of Figure 4) at the same location. The two lower candidate ceramic vane contours have smaller maximum-to-trailing edge thickness ratios than the metallic vane contour to reduce thermal shock stresses. The ceramic vane contours also have greater camber to increase their cross section minimum moment of inertia and, consequently, bending stiffness to values equivalent to (for bottom shape) or greater than (for middle shape), that of the metallic vane cross section. Screening thermal and stress analyses will be used to choose the airfoil shape for the ATS turbine second-stage ceramic vane.

APPLICATION

Elimination of second-stage vane cooling flows by use of ceramic vanes could result in an about 0.35 percentage point increase in overall engine efficiency and an about 670 horsepower increase in output compared to the all-metallic 701-K (ATS) turbine. Potential economic benefits to the owner of the 701-K (ATS) turbine with uncooled ceramic second-stage vanes and corresponding increased performance were calculated. The value to the user of the engine with ceramic vanes in a generation plant was calculated to be $192,000 greater than the value for the all-metallic 701-K turbine.

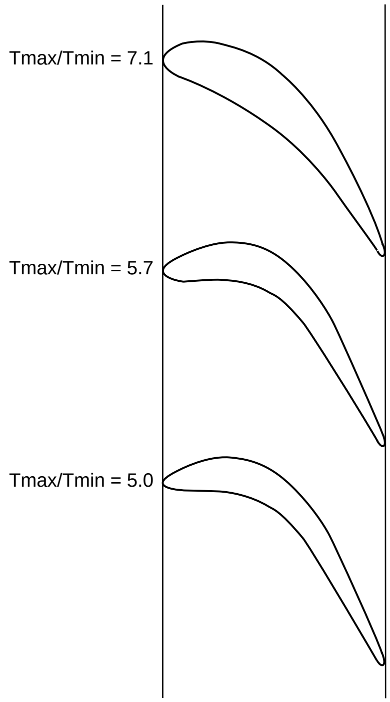

Figure 4. Ceramic versus metallic vane contours.

FUTURE ACTIVITIES

Delivery of the 501-K turbine ceramic vanes is scheduled to be completed by the end of August, 1998. Following completion of vane thermal shock and engine tests at Allison, the 501-K turbine ceramic vane field demonstration is scheduled to start in early 1999.

ACKNOWLEDGMENTS

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